Physics of the Earth and Planetary Interiors, 72 (1992) 264–275
Elsevier Science Publishers B.V., Amsterdam

# Further evidence for the 'Lay discontinuity' beneath northern Siberia and the North Atlantic from short-period P-waves recorded in France

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(Accepted 22 January 1992)

ABSTRACT

Houard, S. and Nataf, H.-C., 1992. Further evidence for the 'Lay discontinuity' beneath northern Siberia and the North Atlantic from short-period P-waves recorded in France. Phys. Earth Planet. Inter., 72: 264–275.

We analyze data from the French Laboratoire de Detection Geophysique (LDG) network of digital short-period seismic stations. The P-waves from several earthquakes in the Kuril–Okhotsk region display clear secondary arrivals in the 75–85° range, which are not explained by smooth lower mantle models. The move-out of the arrivals across the network indicates a deep mantle origin. We interpret them as waves reflected off, or transmitted at, the 'Lay discontinuity', about 300 km above the core–mantle boundary. The bounce points at this discontinuity are located beneath northern Siberia, slightly to the northwest of the region for which a similar structure has been reported. We propose tools for investigating the lateral variations of the D″ structure on the scale 100–1000 km. The method we propose is based on the deconvolution of the data, or convolution of synthetics, by a source time function derived from the data. We show that the method helps identification of the waves that interact with the 'Lay discontinuity', and enables a more objective mapping of its lateral variations. Evidence for bumps a few kilometers high on the lateral scale of a few tens of kilometers is proposed. We also probe a spot of the lower mantle beneath the North Atlantic. A detailed analysis of the waveforms from a Chiapas earthquake suggests that the 'Lay discontinuity' is also present in that part of the world.

## 1. Introduction

The D″ region, at the base of the mantle, is of considerable interest for many branches of the earth sciences. It has long been recognized as a rather anomalous and heterogeneous region (Gutenberg, 1914; Bullen, 1949; Wright and Cleary, 1972; Dziewonski, 1984). But study of its structure has been renewed with the discovery, by Thorne Lay and coworkers, of a discontinuity at its top, some 200–300 km above the core–mantle boundary (Lay and Helmberger, 1983a,b; Zhang and Lay, 1984; Young and Lay, 1987; Garnero et al., 1988; Young and Lay, 1990).

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There are several features of this discontinuity that are quite interesting:

(1) it is not present everywhere on the globe (Schlittenhardt et al., 1985; Garnero et al., 1988);

(2) it is sometimes visible with S-waves and not with P-waves, and vice versa (Baumgardt, 1989; Lay, 1989; Weber and Davis, 1990);

(3) its depth seems to vary by up to 100 km (Lay, 1989; Weber and Körnig, 1992);

(4) its nature is unknown.

All these characteristics suggest that there might be a link between the structure at the top of D″ and geodynamical processes. If the material in D″ is chemically distinct from the mantle above (Jordan, 1979; Silver et al., 1988; Knittle and Jeanloz, 1989), the interface would be deformed by convection currents (Hansen and Yuen, 1989). If the discontinuity marks a phase transition (Anderson, 1987; Stixrude and Bukowinski, 1990), its existence and position would depend upon temperature. In both cases, we expect large variations to occur on the scale of these geodynamical processes. Boundary-layer instabilities, which might be at the origin of hotspots (Morgan, 1972; Yuen and Peltier, 1980), are expected to be features a few hundred kilometers wide (Morgan, 1971; Loper and Stacey, 1983), separated by distances of the order of a thousand kilometers (Fleitout and Moriceau, 1992). It is, therefore, of interest to try to probe D″ at this scale of 100–1000 km.

In this paper, we present P-wave data from the short-period digital Laboratoire de Detection Geophysique (LDG) network, in France. The next section describes this original network. We then present the method used to compute synthetics (Chapman's WKBJ algorithm). Then we show

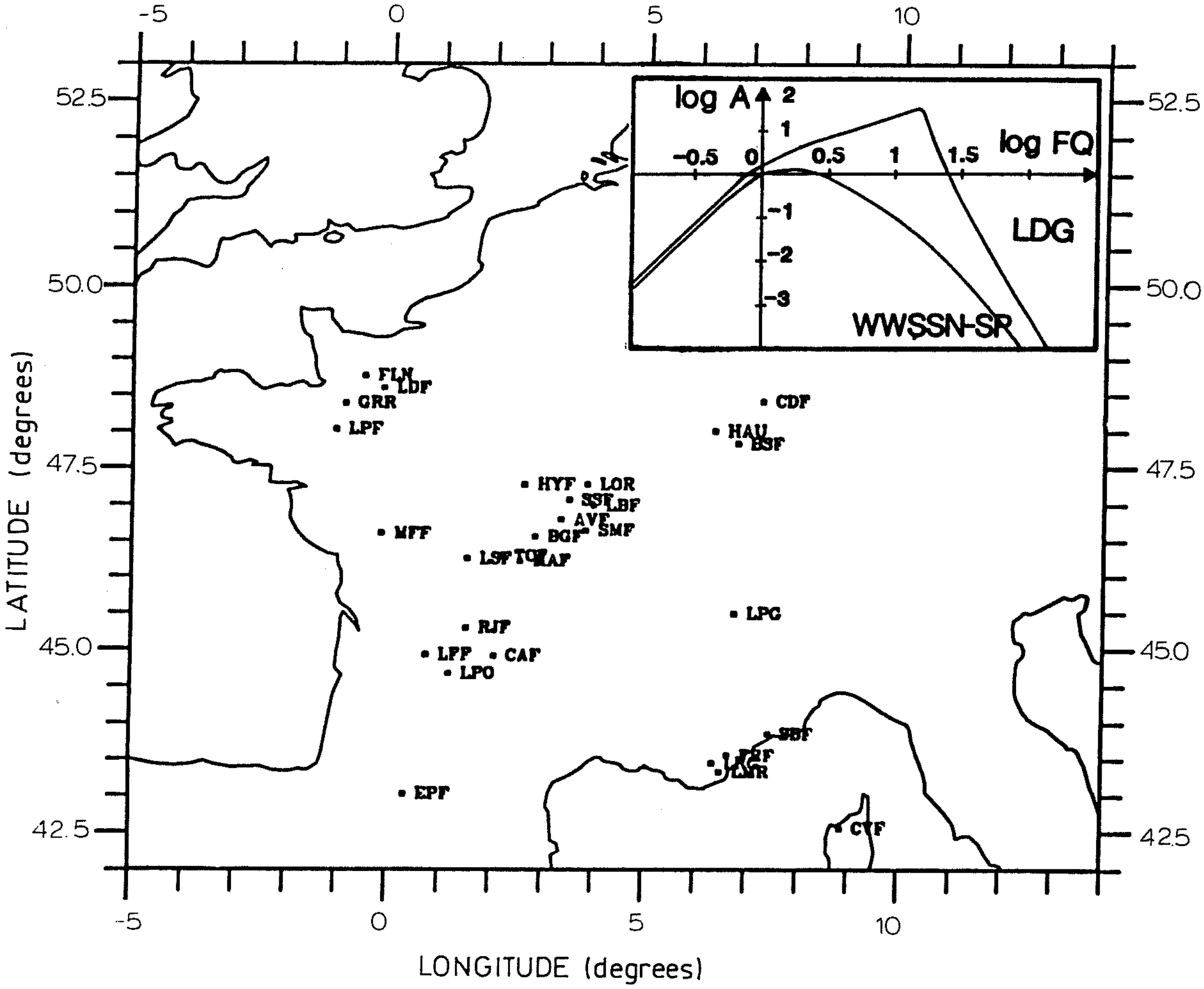


Fig. 1. Map of the French seismic LDG network. It consists of about 30 permanent short-period stations equipped with the same vertical component seismograph. The insert at the top right of the figure displays both LDG and WWSSN short-period instrumental displacement responses. The LDG response is characterized by a maximum of sensitivity around 12 Hz, far beyond the one for the classical WWSSN-SP instrument. Not displayed on this map is the LPL station, which is only 1.5 km away from the LPG station.

data from a Kuril event, from which waves reflected off the 'Lay discontinuity' can be followed easily. As a further step, we propose to deconvolve the data by a source time function derived from the data, and to convolve the synthetics with this same time function.

This approach is illustrated with records from two Okhotsk earthquakes. Evidence for lateral variations at a regional scale is given. The last section presents a similar approach applied to a Chiapas event, which appears to have a fairly complex source history. It is inferred that the 'Lay discontinuity' is also present beneath a spot of the North Atlantic.

## 2. The LDG network

We analyze data from the seismic network run by the LDG of the French Atomic Energy Commission (CEA). First installed around 1960, it has provided digital data from about 30 stations since 1974 (Massinon and Plantet, 1976). Figure 1 shows the location of the stations. All sites are on crystalline bedrock and are equipped with the same type of seismograph vertical. The total displacement response of the instrument, built by the CEA, is inserted in Fig. 1, and compared with that of the classical short-period World-Wide Standard Seismograph Network (WWSSN) instrument. Note the maximum sensitivity around 12 Hz. All data are radio-transmitted in real time to the LDG data center, with a sampling rate of 50 $s^{-1}$. Even though the geodynamical context varies substantially from station to station, the LDG network appears to be quite homogeneous, and is well suited for investigating deep mantle structure on the 100–1000 km lateral scale.

## 3. WKBJ synthetics

If there is a discontinuity at the top of D″, we should observe in the travel time vs. distance plots the usual triplication signature, with a P-wave that travels above the discontinuity (PnLayP), one that is transmitted below (PtLayP), and one that is reflected off the discontinuity (PrLayP). When these waves arrive at almost the same time they interfere with each other making it difficult to identify individual arrival times, and it is necessary to compute synthetic seismograms for comparison with the data.

We apply the WKBJ method (Chapman, 1976, 1978; Dey-Sakar and Chapman, 1978; Chapman and Orcutt, 1985a) to compute these synthetics. We use software provided by Chapman et al. (1988). This method is based on a high frequency approximation that is quite good for the LDG type of data. This approximation makes the WKBJ theory a generalized ray theory. As the number of rays to be computed in this study is small (even more with deep events like ours), the WKBJ method is much less time consuming than global response methods like reflectivity (Kennett, 1983). We include rays for the three waves mentioned above, and for PcP. In tests, we also included the ray for a wave that gets transmitted down at the 'Lay discontinuity', is bent up, and gets reflected down at the discontinuity, before bending up to the surface. It had little effect on the waveform, and is not included in the synthetics presented in this paper.

The impulse response synthetics are computed for the PWDK 'Lay discontinuity' model of Weber and Davis (1990). This model is characterized by a 3% jump in P-wave velocity 290 km above the core–mantle boundary. The 'Lay discontinuity' structure is connected to the Preliminary Reference Earth Model (PREM) (Dziewonski and Anderson, 1981) velocity structure: below at the core–mantle boundary, and 300 km above through a slight velocity gradient. We assumed a 3% jump for both S-wave and density, at the same depth as for P-waves.

As will be seen below, we obtain realistic synthetic seismograms by convolving the impulse response synthetics with a stacked signal derived from the data. The stacked signal accounts for the source time function and amplitude, attenuation, and instrument response (as well as some average site responses, possibly). Implicit is the assumption that attenuation is the same for all ray-paths considered here, which is reasonable because of their proximity.

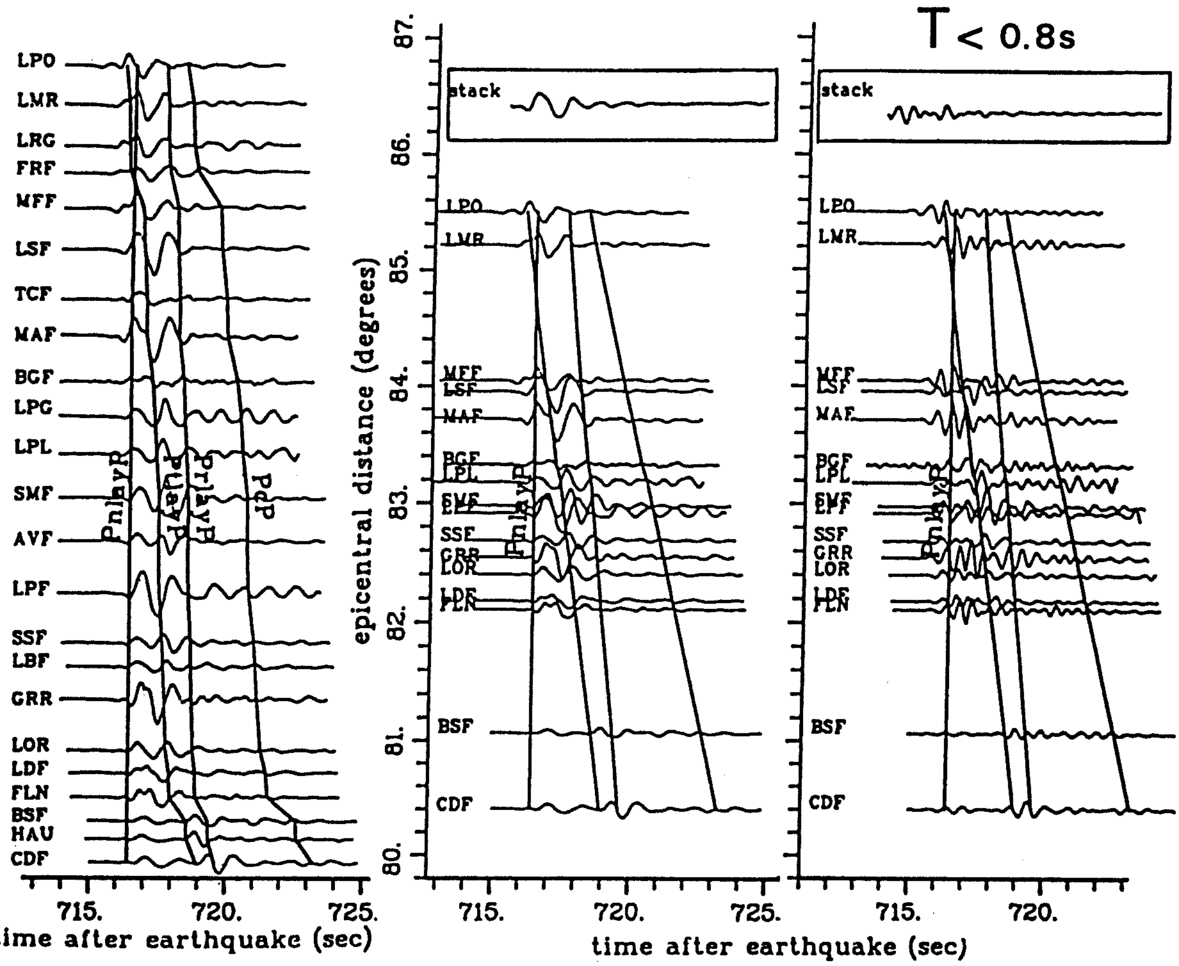


Fig. 2. Seismograms for the Kuril earthquake of 23 September, 1987. In all three panels, records are aligned on the theoretical PnLayP arrival. The time scale applies to the station closest to the earthquake (the bottom one). Left panel: amplitude plot for 23 stations of the network. The stations are arranged in order of increasing epicentral distance from the bottom to the top of the figure. Also displayed are the theoretical travel time curves for waves PnLayP, PtLayP, PrLayP, and PcP. Middle panel: *T*-Delta plot for a selection of stations. The stacked seismogram (see text) is shown above, at the same time scale. Right panel: same as the middle panel, but once a butterworth high-pass filter ($T < 0.8$ s) has been applied to the signals. Note the clear arrivals at stations CDF and BSF.

TABLE 1

Earthquakes' parameters from preliminary determination of epicenters (PDE) bulletins (focal mechanisms from P wave first motions)

| Date | Time (h, m, s) | Lat. (deg) | Long. (deg) | Depth (km) | mb | Focal mechanism | | | Region |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Strike (deg) | Dip (deg) | Slip (deg) | |
| 15/09/1983 | 10:39:02 | 16.1 | −93.1 | 115 | 5.6 | 350 | 83 | −90 | Chiapas |
| 01/02/1984 | 07:28:29 | 49.0 | 146.6 | 573 | 6.0 | 232 | 82 | 66 | Okhotsk |
| 14/07/1987 | 23:46:04 | 49.6 | 147.8 | 576 | 5.6 | 201 | 78 | 90 | Okhotsk |
| 23/09/1987 | 07:15:43 | 46.0 | 149.5 | 131 | 5.9 | 57 | 70 | −147 | Kuriles |

## 4. Northern Siberia

Using earthquakes in the Kuril–Okhotsk region, recorded at the Graefenberg array, Weber and Davis (1990), and Weber (1992) have shown clear evidence for the 'Lay discontinuity' beneath northern Siberia. However, the discontinuity disappears to the southeast (Weber and Davis, 1990), as well as to the north (Buchbinder, 1990, 1991). We use Kuril–Okhotsk events recorded at the LDG network to probe the existence of the 'Lay discontinuity' northwest of the region investigated by Weber and Davis.

### *4.1. An exceptional event*

Figure 2 shows the seismograms at the LDG stations of the Okhotsk earthquake of 23 September 1987. The earthquake parameters, from PDE, are listed in Table 1. The left panel gives the signal at 23 stations. The signals have been time-shifted, so as to be all aligned on the theoretical PnLayP arrival. The times at the bottom apply to the station closest to the earthquake (CDF). Also marked are the theoretical arrival times of PnLayP, PtLayP, PrLayP, and PcP, computed using the PWDK model.

A second arrival, at a time close to the expected PtLayP or PrLayP, shows up clearly at the Vosgian stations CDF, HAU, and BSF. The middle panel, a $T$–Delta plot of a selection of stations, shows that the move-out with distance agrees well with the predicted move-out for PtLayP or PrLayP. Waveform complexities are observed at many stations, such as FLN, LDF, GRR, LPL, LSF, and MFF. They suggest that several waves might be interfering. The right panel of Fig. 2 shows that, by simply applying a high-pass butterworth filter (period $T < 0.8$ s), we can indeed separate at least two arrivals at almost all stations (see, for example, FLN, LDF, GRR, SSF, LPL, and LSF). The second arrival gets closer to the first one as the epicentral distance increases, ruling out an explanation in terms of source complexity. The move-out is again quite similar to the one predicted for the PrLayP or PtLayP rays computed with the PWDK model. Note that PcP is never visible, except at CDF (and perhaps BSF). It is predicted to be very weak at these distances, as we will show on synthetics below.

There are several circumstances which make this record section rather exceptional.

(1) This earthquake has a very short and simple source time history. We retrieved this source history by carefully aligning all first arrivals of the seismograms, and stacking them. We obtained the seismogram labeled 'stack' in the middle panel of Fig. 2. Signals related to later arrivals or site response presumably cancel out in this procedure. The source duration is only a couple of seconds.

(2) The earthquake is 130 km deep, so that the P-waves travel only once across the highly attenuating uppermost mantle. The good ground coupling of the stations, and the large sensitivity of the LDG instrument at high frequencies, make it possible to retrieve energetic signals with a dominant period of less than 0.5 s (right panel of Fig. 2).

(3) The LDG network appears to be almost on a node of the P-wave radiation pattern, as deduced from the earthquake's focal mechanism (Table 1). This is probably why the second arrival is larger than the first one at stations CDF, HAU, BSF, SMF, LPL, and LSF. This is not predicted by the PWDK synthetics, but the slight difference in take-off angle between PnLayP and PrLayP can move the latter away from the node, thereby inverting the amplitude ratio. Note that this earthquake also yields the best evidence for the 'Lay discontinuity' in Weber and Davis (1990).

Although, in this example, second arrivals, which can be attributed to PtLayP or PrLayP, are present at all stations, there is quite some variability in the amplitude ratios, and in the time separation of the two arrivals as compared with the 'theoretical' ones (compare LSF and MFF, for example). Later arrivals, which are not predicted by the PWDK model, are also observed. These variations might indicate lateral heterogeneities of the kind we are looking for, but working a structural model out is not an easy task.

As a first step towards an objective assessment of the presence, absence, and position of the 'Lay discontinuity', we propose the following approaches.

(1) Deconvolving the stack from the seismograms, in order to remove source effects and assess receiver effects. Amplitudes and arrival times can be measured from these deconvolved signals.

(2) Convolving the stack with synthetic seismograms from a given model (including a D″ layer discontinuity) and comparing them with the data. Cross-correlation of the synthetics with the actual data can help derive a quantitative measure of how good a model is compared with another one.

In both cases, the construction of a good source signal is an essential preliminary step. It is obtained by stacking the LDG seismograms aligned on the first P-wave arrivals using a set of dynamic station corrections calculated for each earthquake (compared to the set of static station corrections described in the Appendix).

We now detail these two approaches, and illustrate them with examples.

### 4.2. *Deconvolving the stack from the data*

Deconvolution is known to be a very unstable operation. Various methods have been proposed to stabilize the solution. In the Wiener optimal filtering method, a noise spectrum is estimated, and used to damp out deconvolved bursts coming

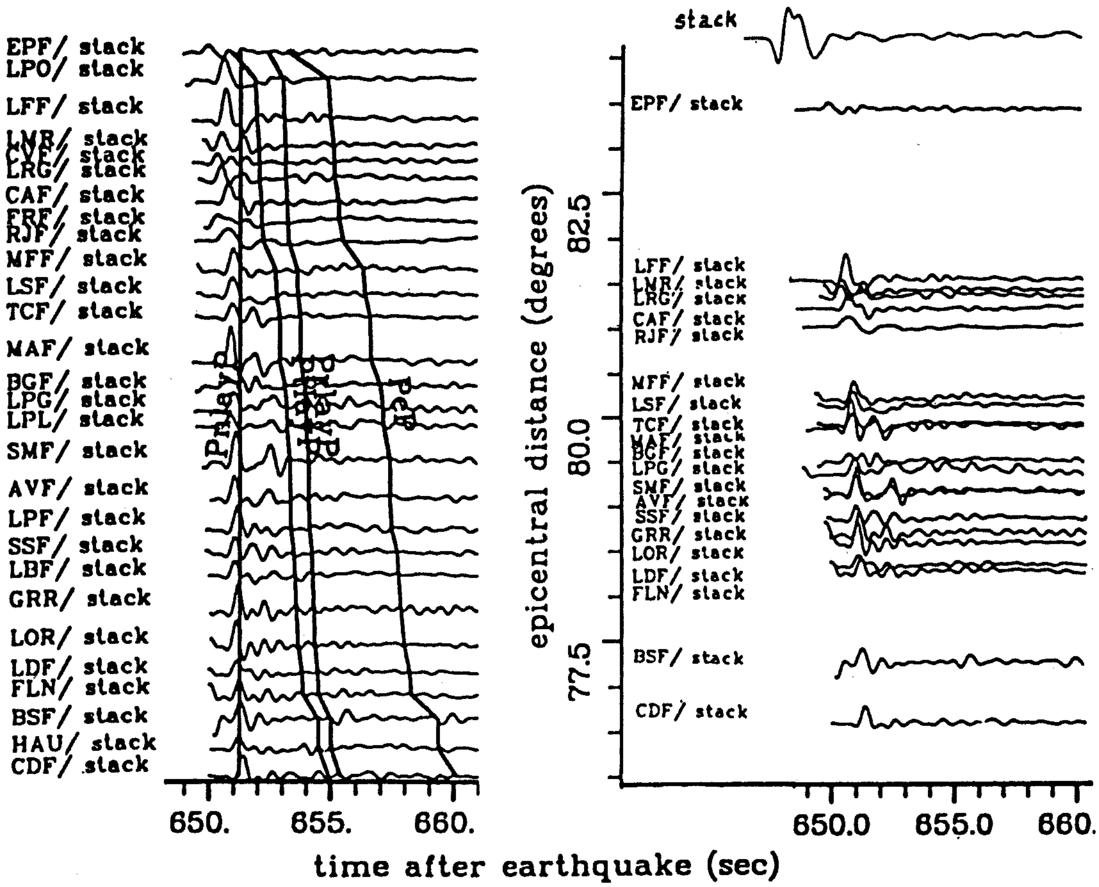


Fig. 3. Seismograms deconvolved by the stack for the Okhotsk earthquake of 14 July 1987. The stack is displayed above the right panel. Same set-up as for Fig. 2. Left panel: amplitude plot for 28 stations of the LDG network. Right panel: *T*-Delta plot for a selection of the previous set of stations. Note the first peak for the PnLayP arrival, and the several secondary peaks indicating other arrivals.

from noise-level signal (see, for example, Press et al., 1986). Here, we have taken a simple approach, similar to an a posteriori Wiener deconvolution: we first apply a straight deconvolution in the frequency domain, and then low-pass the output to obtain a more stable signal. This method gives, in our case, results similar to a more orthodox Wiener deconvolution, with greater flexibility.

Figure 3 shows the signals deconvolved by the stack, derived for the Okhotsk earthquake of 14 July 1987 (see Table 1). The stack (at the top of

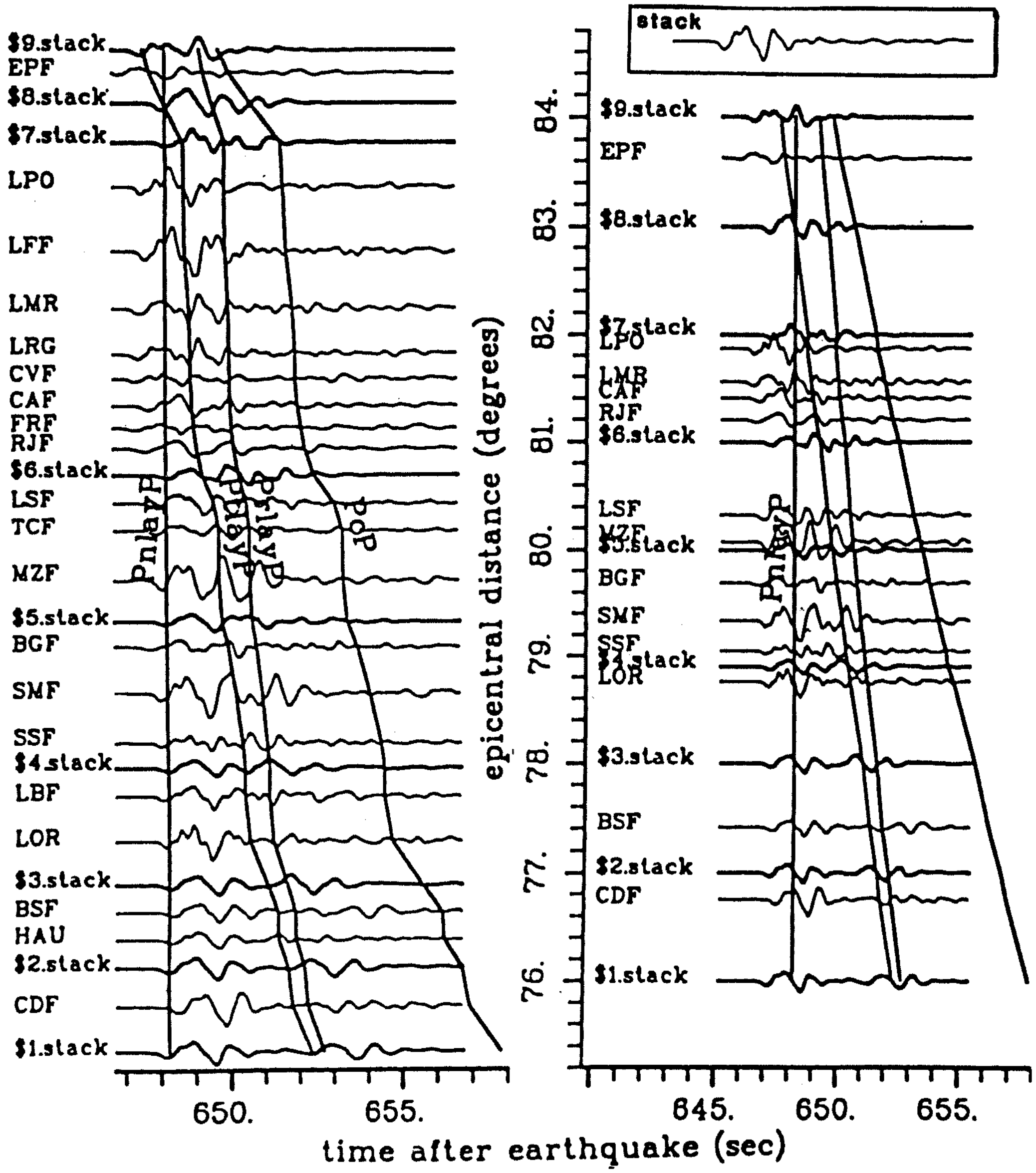


Fig. 4. Comparison of data and synthetic seismograms convolved with the stack, for the Okhotsk earthquake of 1 February 1984. Synthetics are computed with the WKBJ method and with an epicentral distance interval of 1 degree. The stack is displayed above the right panel. Synthetic seismograms are recognizable for their greater line thickness. Same set-up as for Fig. 2. Right panel: amplitude plot comparison. Left panel: *T*-Delta plot comparison for a selection of the previous LDG stations.

the figure) again indicates a fairly simple and short source history. In the left panel are the signals at 28 stations, while the right panel is *T*-Delta plot for a selection of stations. A clear peak marks the first arrival at most stations, while secondary peaks are visible at several of them. Among these, a few indicate a move-out similar to that of PrLayP or PtLayP (CDF, HAU, LBF, AVF, SMF, LPG, MAF, TCF, LFF, and LPO), while other display peaks that are apparently unrelated to D″ structure, but are possibly due to near-receiver structure, or to directional source signals.

### *4.3. Comparing data and synthetics*

Impulse response WKBJ synthetic seismograms computed for model PWDK of Weber and Davis (1990), are convolved with the stack derived from the data. The synthetics are multiplied by a constant factor, in order to yield amplitudes similar to the observed ones. This factor is chosen once for all, since the stacks carry along the information on the size of the source. Similarly, a constant time shift is chosen in order to align the convolved synthetics with the data at our reference station SMF (see the treatment of static station corrections in the Appendix). This time shift is the same for all stations, but it is allowed to change from one earthquake to the next, since it compensates for the mislocation and error in the origin time of the event.

Figure 4 compares synthetics convolved with the stack and data for the Okhotsk earthquake of 1 February 1984. The stack (at the top) indicates a slightly more complex source than for the two preceding events, but still rather well behaved. Secondary arrivals are clearly seen at stations such as CDF, BSF, SSF, and SMF. The synthetic at 77° correlates very nicely with the data at CDF, while the second arrival at BSF is clearly too late. More interesting is the comparison of the waveforms at epicentral distances around 82°. There, the three triplicated waves interfere closely, and the waveform is complex. These complexities are well reflected in the synthetics at 82°, but are also present, and look very similar, at stations LPO and LFF. Also note the cross-over of PnLayP and PtLayP at Delta = 83°, and the agreement between data at EPF and the synthetic at 84°.

By removing the source from the seismograms, we can compare results from different earthquakes. This is one way of checking that the receiver side is not responsible for the phases we interpret as D″ structure. A detailed analysis of the records station by station for the three earthquakes presented so far does confirm that the secondary arrivals are not due to receiver structure (note that the first Moho P reflection would arrive some 10 s after the first arrival, much later than the arrivals we consider here).

An interesting, though puzzling, example is provided by the BSF station. For the 1 February 1984 and 14 July 1987 events, a prominent arrival is observed, some 4.5 s after the first one. However, in both cases, it arrives 1.0–1.5 s later than the PrLayP or PtLayP waves predicted using the PWDK model. Could this arrival be due to receiver structure? No large arrival is seen 4.5 s after the first arrival at BSF for the 23 September 1987 event. The second arrival there is only 2.5 s after the first one, in good agreement with the theoretical arrival time for PrLayP. Therefore, it does not seem likely that the receiver structure is responsible for these secondary arrivals. The late arrival at BSF for the 1 February 1984 and 14 July 1987 events might actually be due to the type of lateral variations of D″ we are looking for. The bounce points of PrLayP for these two records are only 40 km apart (but also only 60 km from the bounce point for the 23 September 1987 event). A local downwarp of the 'Lay discontinuity' might explain the observed delay.

At this stage, we only suggest this as a possibility, and emphasize that the tools we have developed are well suited for a more detailed study of such features [a].

It is interesting to see where the region we probe is situated, especially for comparison with the results of Weber and Davis (1990). Figure 5 gives the geographical position of the bounce points of PrLayP, at the top of D″, for the three

[a] Further investigation along the lines presented in this paper have led us to conclude that the late secondary arrival as BSF is infact a receiver effect.

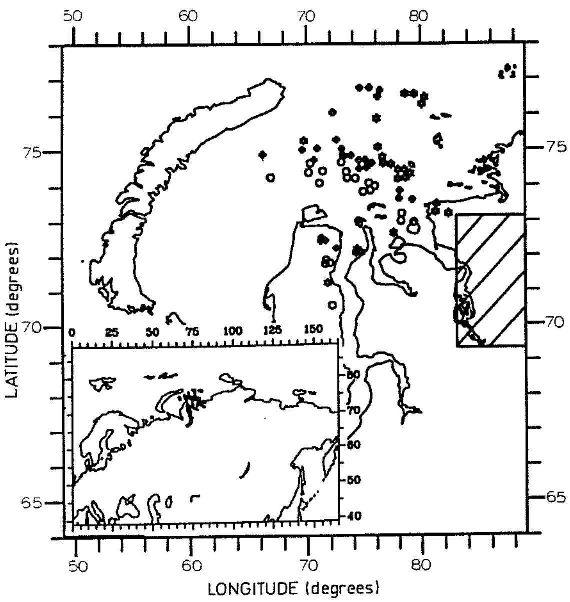


Fig. 5. Map of the bounce points of the PrLayP wave at the top of D″ for the three Okhotsk/Kuril events presented so far (see Table 1 for more information). One symbol is associated with each earthquake and for all stations: circles for the 1 February 1984 event, crosses for the 14 July 1987 event, and stars for the 23 September 1987 event. The hatched rectangle indicates the D″ region sampled by Weber and Davis (1990). The insert replaces the region in a continental-size map.

events we have presented. The region for which Weber and Davis derived the PWDK discontinuity model is indicated by the full square. Our results confirm Weber and Davis' findings, and extend the region where the 'Lay discontinuity' is observed to the northwest. We have mapped the bounce points of PrLayP here. However, from our data, we rarely can distinguish between PrLayP and PtLayP. If we were to map the entry points of PtLayP in D″, they would plot more than 300 km (≈ 3 latitude degrees) away, east and west, from the PrLayP bounce points.

## 5. The North Atlantic

Earthquakes in Central America recorded at the LDG network enable us to probe a completely different region of the world. Figure 6 shows the record section for the Chiapas earthquake of 15 September 1983 (see Table 1). At first sight, we might pick secondary arrivals at LPF, GRR, and FLN, which are close to the arrival times of PrLayP and PtLayP computed from model PWDK. However, as illustrated by the stack at the top of the figure, the source time history of this event is long and complex. Great care must be taken not to misinterpret source complexities as structure. We have computed WKBJ synthetics, and convolved them with the stack.

A close examination of the waveforms at the group of stations LRG, LMR, and FRF, shows that the first energetic train ends with a shoulder, which is not present in the stack, but which is well modeled by the synthetic at 86°. On the other hand, the group LPF, GRR, and FLN, shows a distinct waveform, with a large negative swing 3 s after the beginning of the signal. This swing is not present in the stack. It is visible in the synthetic at 80°, but arrives too late to explain the data. Several stations, such as CVF, SMF, and SSF, show good visual correlation with the closest synthetic, though the PWDK model (Weber and Davis, 1990) has been derived for a completely different region. This can be quantified somewhat, by computing the cross-correlation of the data with the closest synthetic on one hand, and of the data with the stack, on the other hand.

We, therefore, think that the 'Lay discontinuity' is also present beneath that spot of the North Atlantic, possibly at a slightly different depth than beneath northern Siberia. Figure 7 shows the location of the bounce points of PrLayP for this event. However, we need to examine records from earthquakes with a simpler time history, in order to be able to follow the move-out of the secondary arrivals with distance.

## 6. Conclusion

We have investigated the structure of the D″ layer at the base of the mantle, on the 100–1000 km scale, using the short-period seismic network of the LDG, in France. From P-wave records in the epicentral distance range 75–85°, we find clear evidence for the 'Lay discontinuity' beneath northern Siberia. This confirms, and extends to the northwest, the findings of Weber and Davis (1990).

We have developed tools for assessing lateral variations of the depth of discontinuity in a quantitative way. In a first step, we carefully align the first arrivals of all records, and stack them for retrieving the far-field source time history. By deconvolving this source function from the data, we get a peak for each arrival in the record. It is then possible to follow the move-out of the secondary arrivals with respect to the first one, and to identify local deviations. Since the source is in

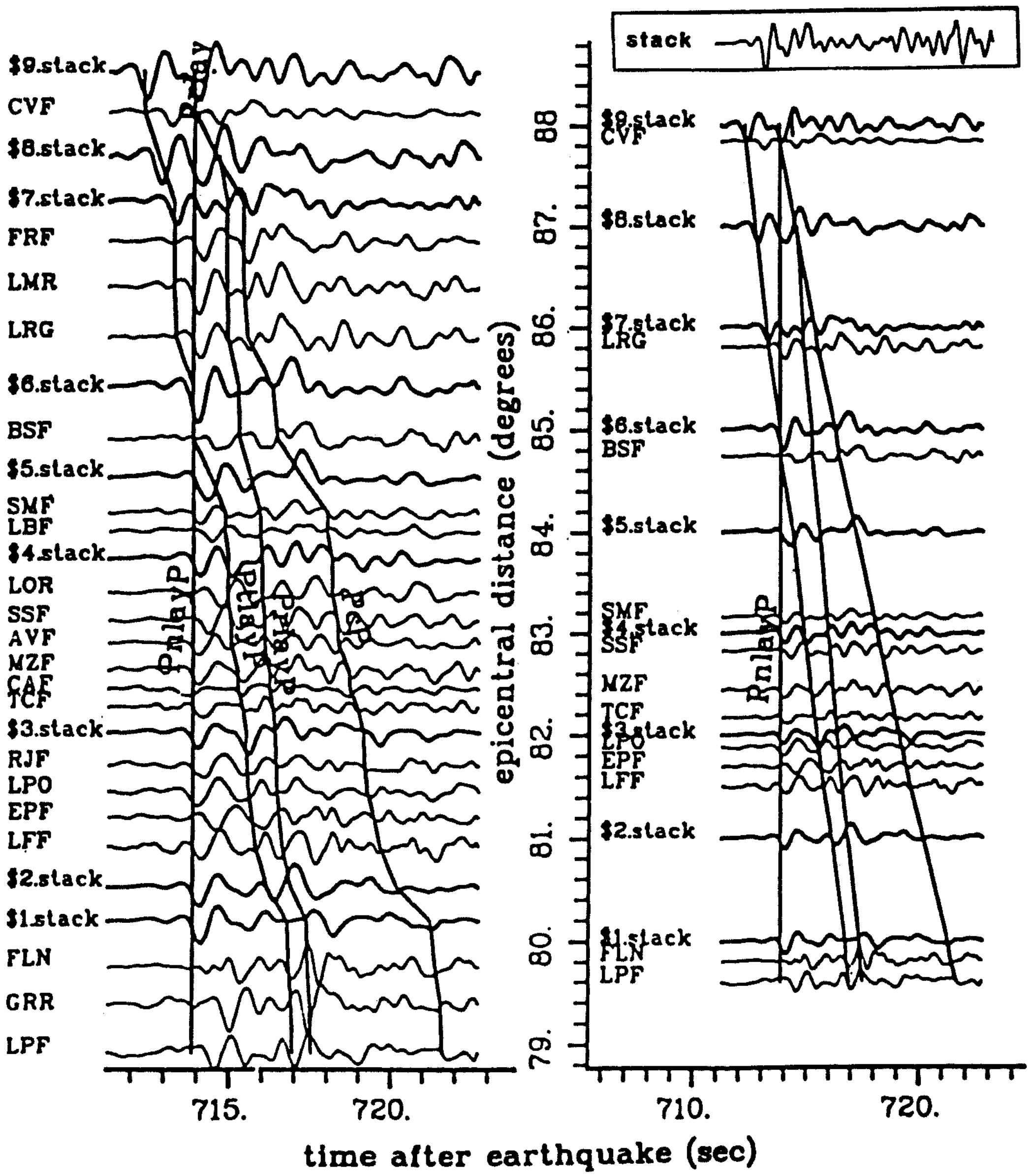


Fig. 6. Comparison between data and synthetics for the Chiapas earthquake of 15 September 1983. The same remarks as for Fig. 4 apply here. Note the complexity of the stack for this event.

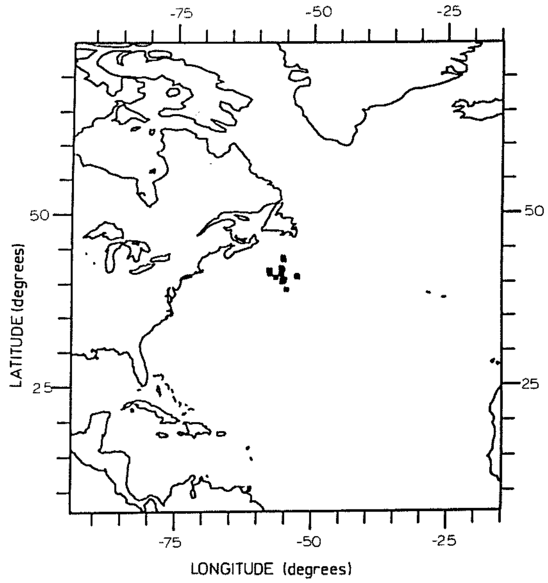


Fig. 7. Map of the bounce points for the Chiapas earthquake of 15 September 1983.

effect removed from the data, it enables a comparison of records from different earthquakes.

In a complementary perspective, the source time function is convolved with the synthetics computed with a given velocity model. Comparisons of these synthetics with the data show that the PWDK model of Weber and Davis (1990) explains several features in the actual waveforms. The agreement between data and synthetics can be quantified by cross-correlation. We are currently using these tools to investigate lateral variations in the structure of D″, on length scales of 100–1000 km, at which we expect signatures of geodynamical phenomena, such as hotspots.

These tools also provide help for identifying waves reflected off the 'Lay discontinuity', especially when the source time history is complex. We think that such waves are visible on records from a Chiapas earthquake, implying that the 'Lay discontinuity' is also present in the North Atlantic. Further investigation is needed to confirm this result.

## Acknowledgments

We are thankful to those who run the LDG network, and in particular to Bernard Massinon and Jean-Louis Plantet, for making the data available to us. We are indebted to Chris Chapman, who has made his WKBJ algorithm available to the community. We thank Annie and Marc Souriau, Thorne Lay, and Michael Weber, for useful discussions. Michael Weber also provided a collection of his preprints prior to publication. This work was supported by Centre National de la Recherche Scientifique (INSU/IST Tomography). ENS Paris-Geologie.

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## Appendix: Static station corrections

In order to compare the arrival times of teleseismic P-waves at the different stations, we need to remove time variations due to local structure beneath the station. Since we are mainly interested in getting the relative times between stations, and mostly for earthquakes from one geographical region, we have computed our own static station corrections. We have used the P-arrival times reported to ISC by LDG for the years 1982–1987, for earthquakes in the Kuril, Sea of Japan, and Sea of Okhotsk regions. Software and CD-Rom data are from the National Earthquake Information Center (NEIC) data center, via ORFELIS.

Only earthquakes observed at more than 99 stations world-wide were retained. We thus obtained 282 arrival times for the best reporting station of the LDG network: SMF. This became our reference station, and relative time-arrival deviations were computed for all stations relative to SMF. They range from $-0.44 \pm 0.31$ at BSF, to $0.90 \pm 0.39$ at LPL and LPG. All records presented in this paper (including the ones for the Chiapas earthquake), have had these corrections applied. Note that, for computing the stack, the first arrivals of all records are aligned, irrespective of the static station corrections, using this time a set of dynamic station corrections.